

A SEARCH FOR THE FOURTH SM FAMILY FERMIONS AT $\mu^+\mu^-$ COLLIDERS

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The potential of $\mu^+\mu^-$ colliders to investigate the fourth SM family fermions predicted by flavour democracy has been analyzed. It is shown that muon colliders are advantageous for both pair production of fourth family fermions and resonance production of fourth family quarkonia.

1 Introduction

The mass spectrum and the mixing of fundamental fermions are the most important unsolved problems of the particle physics. According to the Standard Model (SM), these masses and mixings arise from the interaction with the Higgs doublet via spontaneous symmetry breaking.

In the framework of SM, fermions with the same quantum numbers (electric charge, weak isospin, etc.) are indistinguishable before the symmetry breaking. Therefore, in the fermion-Higgs interaction, the Lagrangian terms corresponding to fermions with the same quantum numbers should come with equal strength. As a result, one deals with singular mass matrices after the spontaneous symmetry breaking.

According to DMM (Democratic Mass Matrix) approach ^{1,2,3,4,5} in the case of n SM families ($n - 1$) families are massless and n^{th} family fermions have masses $na\eta$ (here a is the common strength of Higgs-fermion interactions). Taking the real mass spectrum of the third family fermions into account necessarily leads to the assumption that at least a fourth SM family must exist ^{6,7,8}. For recent situation see Ref. ⁹.

The existence of the fourth SM family and masses of the fourth SM family quarks will be determined as a result of experiments done at LHC ^{10,11}. In our opinion, muon colliders will be advantageous for investigation of the fourth SM family leptons and quarkonia.

2 The Production of the Fourth SM Family Fermions at $\mu^+\mu^-$ Colliders

It is clear that direct pair production of the fourth family fermions will be possible at future high energy colliders only, since their predicted masses lie between 300 GeV and 700 GeV ⁷. Therefore, lepton colliders with $\sqrt{s} \geq 1.5\text{ TeV}$ and sufficiently high luminosity will give the opportunity to search for all fermions from the fourth SM family.

Linear e^+e^- colliders with high energy are ones of the necessary devices to search the fundamental ingredients of matter and interactions of them. But the advantage of $\mu^+\mu^-$

Table 1. The production cross section values for the fourth SM family fermions.

M_4 (GeV)	$\mu^+\mu^- \rightarrow u_4 \bar{u}_4$		$\mu^+\mu^- \rightarrow d_4 \bar{d}_4$		$\mu^+\mu^- \rightarrow l_4^+ l_4^-$		$\mu^+\mu^- \rightarrow \nu_4 \bar{\nu}_4$	
	$\sigma(fb)$	Ev./year	$\sigma(fb)$	Ev./year	$\sigma(fb)$	Ev./year	$\sigma(fb)$	Ev./year
300	9.8	490	5.0	250	6.1	305	1.3	65
375	9.7	485	5.0	250	6.1	305	1.3	65
450	9.7	485	4.9	245	6.1	305	1.3	65
525	9.6	480	4.8	240	6.1	305	1.3	65
675	9.5	475	4.7	235	6.0	300	1.2	60
750	9.4	470	4.6	230	6.0	300	1.2	60

colliders with respect to e^+e^- colliders is that, they have more monochromatic particle beams. For example, while the energy spread of e^+e^- colliders is more than 1%, that of $\mu^+\mu^-$ colliders is between 0.1% and 0.014%. In addition, since the mass of muon is 207 times more than the mass of electron, the energy uncertainty from effect of the opposite beam can be ignored. Design values of $\mu^+\mu^-$ colliders are $\sqrt{s} = 4 \text{ TeV}$ and $L = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ or $\sqrt{s} = 30 \text{ TeV}$ and $L = 3 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ ¹².

The cross section for the process $\mu^+\mu^- \rightarrow f \bar{f}$ has the form

$$\sigma = \frac{2\pi\alpha^2}{3s} \xi \beta \{ Q_f (Q_f - 2\chi_1 v v_f) (3 - \beta^2) + \chi_2 (1 + v^2) [v_f^2 (3 - \beta^2) + 2\beta^2 a_f^2] \} \quad (1)$$

where

$$\chi_1 = \frac{1}{16 \sin^2 \theta_W^2 \cos \theta_W} \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

$$\chi_2 = \frac{1}{256 \sin^4 \theta_W^4 \cos \theta_W} \frac{s^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

$$v = -1 + 4 \sin^2 \theta_W$$

$$a_f = 2T_{3f}$$

$$v_f = 2T_{3f} - 4Q_f^2 \sin \theta_W$$

$$\beta = \sqrt{1 - 4m_Q^2/s}.$$

$$T_3 = \frac{1}{2} \text{ for } \nu_4 \text{ and } u_4, T_3 = -\frac{1}{2} \text{ for } l_4 \text{ and } d_4$$

$$\xi = 1 \text{ for leptons, } \xi = 3 \text{ for quarks.}$$

The production cross section values and corresponding event numbers (with $\sqrt{s} = 4 \text{ TeV}$ and $L^{int} = 50 \text{ fb}^{-1}$) are given in Table 1.

3 The Production of the Fourth SM Family $\psi_4 (^3S_1)$ Quarkonia at $\mu^+\mu^-$ Colliders

Differing from t-quarks, fourth family quarks can form the quarkonia since u_4 and d_4 are almost degenerate and their decays are suppressed by small CKM mixings ⁸.

The cross section for the formation of the fourth family quarkonium and its decay into

Table 2. The production cross section values and event numbers per year for the fourth SM family quarkonia.

$M_{\psi_4} (GeV)$	$\sigma^{res} (pb)$	$\Gamma_{tot}(\psi_4) (MeV)$	$\Delta E_{coll} (GeV)$	$\sigma^{ave} (pb)$	$Ev./year$
600	68.2	8.3	0.60	0.94	7100
750	19.5	21.1	0.75	0.55	5200
900	6.8	46.9	0.90	0.35	4000
1050	2.8	93.3	1.05	0.25	3300
1200	1.3	170.5	1.20	0.18	2800
1350	0.6	291.6	1.35	0.13	2200
1500	0.3	472.6	1.50	0.09	1800

any X state is given with the relativistic Breit-Wigner equation

$$\sigma(\mu^+\mu^- \rightarrow (Q\bar{Q}) \rightarrow X) = \frac{12\pi (s/M^2) \Gamma_{\mu\mu} \Gamma_X}{(s - M^2)^2 + M^2 \Gamma^2}. \quad (2)$$

Where X corresponds to final state particles, M is the mass of the fourth family quarkonium, $\Gamma_{\mu\mu}$, Γ_X and Γ correspond to partial decay width to $\mu^+\mu^-$, X state particles and the total decay width of the fourth family quarkonium, respectively.

Since the $\mu^+\mu^-$ colliders has the certain energy spread, the average cross section can be estimated from

$$\sigma^{ave} = \frac{\Gamma_{tot}}{\Delta E_{coll}} \sigma^{res}(\mu^+\mu^- \rightarrow (Q\bar{Q})), \quad (3)$$

where σ^{res} is the resonance value of the cross section¹³.

The energy spread is $\Delta E_{coll} \approx 10^{-3}\sqrt{s}$ for the $\mu^+\mu^-$ collider with $\sqrt{s} = \mathcal{O}(TeV)$. The estimated cross section values for $\psi_4(u_4\bar{u}_4)$ are presented in the Table 2. Correspondin values for $\psi_4(d_4\bar{d}_4)$ are approximately the same.

The value of the luminosity at the resonance, used in calculations, has been estimated as

$$L(\sqrt{s_{res}}) = \frac{\sqrt{s_{res}}}{4TeV} L(4TeV).$$

As a result, we obtain number of events per year which are given in the last column of the Table 2.

In this study we consider only $\psi_4(^3S_1)$ quarkonia state. Using corresponding formulae from¹³, we obtain decay widths for main decay modes of $\psi_4(u_4\bar{u}_4)$ which are given in Table 3. One can see that dominant decay modes for ψ_4 quarkonia are $\psi_4 \rightarrow W^+W^-$, $\psi_4 \rightarrow Z^0\gamma$ and $\psi_4 \rightarrow \gamma H$.

Table 3. Decay widths for main decay modes of $\psi_4 (u_4 \bar{u}_4)$, for $m_H = 150$ GeV.

M_{ψ_4} , GeV	600	750	900	1050	1200	1350	1500
$\Gamma(\psi_4 \rightarrow \ell^+ \ell^-), 10^{-2}$ MeV	1.4	1.6	1.8	2.0	2.1	2.3	2.5
$\Gamma(\psi_4 \rightarrow u \bar{u}), 10^{-2}$ MeV	2.3	2.6	3.0	3.3	3.5	3.8	4.1
$\Gamma(\psi_4 \rightarrow d \bar{d}), 10^{-2}$ MeV	1.0	1.2	1.3	1.5	1.6	1.7	1.8
$\Gamma(\psi_4 \rightarrow Z\gamma)$, MeV	0.4	0.7	1.1	1.7	2.4	3.3	4.4
$\Gamma(\psi_4 \rightarrow ZZ), 10^{-2}$ MeV	4.0	7.6	12.6	19.2	27.6	38.0	50.1
$\Gamma(\psi_4 \rightarrow ZH), 10^{-2}$ MeV	4.3	7.9	13.0	19.6	28.1	38.5	51.1
$\Gamma(\psi_4 \rightarrow \gamma H), 10^{-2}$ MeV	36.1	66.3	108.5	164.2	234.8	321.9	426.8
$\Gamma(\psi_4 \rightarrow W^+ W^-)$, MeV	6.8	18.9	43.6	88.7	164.4	283.6	462.4

4 Conclusion

We have shown that $\mu^+ \mu^-$ collider with $\sqrt{s} = \mathcal{O}(TeV)$ is a good place to investigate both fourth family fermions and quarkonia. In this study we have concentrated on $\psi_4 (^3S_1)$ state, other quarkonium states will be considered on future study.

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